

# Standard Solar Neutrinos and The Standard Solar Model

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## Abstract

The standard solar model (SSM) yield a  $^8\text{B}$  solar neutrino flux which is consistent within the theoretical and experimental uncertainties with that observed at Super-Kamiokande. The combined results from the Super-Kamiokande and the Chlorine solar neutrino experiments do not provide a solid evidence for neutrino properties beyond the minimal standard electroweak model. The results from the Gallium experiments and independently the combined results from Super-Kamiokande and the Chlorine experiment imply that the  $^7\text{Be}$  solar neutrino flux is strongly suppressed compared with that predicted by the SSM. This conclusion, however, is valid only if the neutrino absorption cross sections near threshold in Gallium and Chlorine do not differ significantly from their theoretical estimates. Such a departure has not been ruled out by the Chromium source experiments in Gallium. Even if the  $^7\text{Be}$  solar neutrino flux is suppressed compared with that predicted by the SSM, still it can be due to astrophysical effects not included in the simplistic SSM. Such effects include spatial and/or temporal variations in the temperature in the solar core induced by the convective layer through g-modes or by rotational mixing in the solar core, and dense plasma effects which may strongly enhance p-capture by  $^7\text{Be}$  relative to e-capture. The new generation of solar observations, which already look non stop deep into the sun, like Super-Kamiokande through neutrinos, and SOHO and GONG through acoustic waves, may be able to point at the correct solution; astrophysical solutions if they detect unexpected temporal and/or spatial behaviour, or particle physics solutions if Super-Kamiokande detects characteristic spectral distortion or temporal variations (e.g., the day-night effect) of the  $^8\text{B}$  solar neutrino flux. If Super-Kamiokande will discover neither spectral distortions nor time dependence of the  $^8\text{B}$  solar neutrino flux then, only future solar neutrino experiments such as SNO, BOREXINO and HELLAZ, will be able to find out whether the solar neutrino problem is due to neutrino properties beyond the minimal standard electroweak model or whether it is just a problem of the too simplistic standard solar model.

# 1 Introduction

Solar neutrinos have been detected on Earth in four pioneering solar neutrino ( $\nu_\odot$ ) experiments, in roughly the expected numbers, demonstrating that the sun is indeed powered by fusion of hydrogen into helium. However the precise counting rates in these experiments are significantly below (see, e.g., Gavrin, these proceedings, Suzuki 1997) those predicted by traditional Standard Solar Models (SSM) (see, e.g., Bahcal and Pinsonneault 1995; Castellani et al. 1997). This discrepancy, which has persisted for 25 years, has become known as the solar neutrino problem (SNP). It has attracted much attention of both astrophysicists and particle physicists for two main reasons. First, astrophysicists were surprised to find out that the nuclear reaction rates inside the sun deviate significantly from that predicted by the simple SSM. Second, particle physicists found that natural extensions of the minimal standard electroweak model (SEM) can solve elegantly the SNP. However, when astronomers had a closer look at the sun through helioseismology, X-ray and UV observations it turned out to be “a bewildering turmoil of complex phenomena”, showing unexpected features and behavior at any scale. It has a strange complex internal rotation, unexplained magnetic activity with unexplained 11 year cycle, unexpected anomalies in its surface elemental abundances, unexplained explosions in its atmosphere and unexplained mechanism that heats its million degree corona and accelerates the solar wind. Perhaps the surface of the sun is complex because we can see it and the center of the sun is not only because we cannot? Perhaps the SSM which has been improved continuously over the past three decades (see e.g., Clayton 1968, Bahcall 1989), which still assumes spherical symmetry, no mass loss or mass accretion, no angular momentum loss or gain, no differential rotation and zero magnetic field through the entire solar evolution, is a too simplistic picture and does not provide a sufficiently accurate description of the core of the sun and/or the neutrino producing reactions there?

Indeed, here I will show that the solar neutrino problem does not provide solid evidence for neutrino properties beyond the SEM and that standard physics solutions to the SNP are still possible. In particular I will argue that:

1. The  $^8\text{B}$  solar neutrino flux predicted by the standard solar model (SSM) is consistent within the theoretical and experimental uncertainties with that observed at Super-Kamiokande.
2. There is no solid evidence for a real deficit of  $^7\text{Be}$  solar neutrinos.
3. A real deficit of  $^7\text{Be}$  solar neutrinos, if there is one, may still be explained by standard physics and/or astrophysics.
4. Only direct observations of spectral distortions and/or flavor change of  $\nu_\odot$ 's in future

$\nu_\odot$  experiments, like Super-Kamiokande, SNO, Borexino and HELLAZ may establish that neutrino properties beyond the SEM are responsible for the SNP.

5. The three new solar “observatories”, which are already running and looking into the solar interior, the Super-Kamiokande solar neutrino observatory that began taking data on April 1, 1996, the solar heliospheric observatory (SOHO) that was launched on December 2, 1995 and is now observing the sun non stop, and the ground based telescopes in the Global Oscillations Network Group (GONG) which have just begun observing solar oscillations around the clock (for general reviews see Science, 31 May 1996), may very soon point at the correct solution to the SNP.

## 2 Is There a $^8\text{B}$ Solar Neutrino Problem?

Table I presents a comparison between the solar neutrino observations and the SSM predictions of Bahcall and Pinsonneault 1995 (BP95) and of Dar and Shaviv 1996 (DS96). Although BP (and some other similar SSM calculations) predict a  $^8\text{B}$  solar neutrino flux that is approximately 2.6 larger than observed by Super-Kamiokande,  $\phi_{\nu_e} = 2.51 \pm 0.14(\text{stat.}) \pm 0.18(\text{syst.}) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ , (Suzuki 1997), DS predict a flux consistent with that observed by Super-Kamiokande. The differences between BP and DS are summarized in Table II (for details see Dar and Shaviv 1996). The difference between the predicted  $^8\text{B}$  flux are mainly due to the use of updated nuclear reaction rates by DS, differences in the calculated effects of diffusion, differences in the initial solar composition assumed in the two calculations and the use of updated equation of state by DS. They reduce the predicted  $^8\text{B}$  flux approximately by factors of 0.55, 0.81, 0.95 and 0.96, respectively (the remaining differences are mainly due to inclusion of partial ionization effects, premain sequence evolution and deviations from complete nuclear equilibrium by DS which were neglected by BP, and due to different numerical methods, fine zoning and time steps used in the two calculations):

### Nuclear Reaction Rates:

The uncertainties in the nuclear reaction rates at solar conditions are still large due to (1) uncertainties in the measured cross sections at laboratory energies, (2) uncertainties in their extrapolations to solar energies, (3) uncertainties in dense plasma effects (screening, correlations and fluctuations) on reaction rates. Rather than averaging measured cross sections that differ by many standard deviations, DS used for the extrapolation only the most recent and consistent measurements of the relevant nuclear cross sections. Because sub-Coulomb reactions take place when the colliding nuclei are far apart, the Optical Model and the Distorted Wave Born Approximation give a reliable description of their energy dependence. DS

have used them for extrapolating measured sub-Coulomb cross sections to solar energies. BP preferred to rely on published extrapolations of averaged cross sections based on energy dependences calculated from microscopic nuclear reaction models (e.g. Johnson et al 1992). Similar screening corrections (which by accidental cancellation have a very small net effect on  $\phi_{\nu_{\odot}}(^8\text{B})$ ) have been used by DS and BP. The updated “astrophysical S factors” which were used by DS are listed in Table II. They reduce the BP predictions by approximately a factor of 0.55.

**Diffusion:** Diffusion, caused by density, temperature, pressure, chemical composition and gravitational potential gradients play an important role in the sun since it modifies the local chemical composition in the sun. The relative changes in SSM predictions due to diffusion of all elements are summarized in Table III. While BP found a rather large increases in the predicted  $^7\text{Be}$ ,  $^8\text{B}$ ,  $^{13}\text{N}$ ,  $^{15}\text{O}$  and  $^{17}\text{F}$  solar neutrino fluxes; 14%, 36%, 52%, 58%, and 61% which result in 36%, 33%, 9% increases in their predicted rates in Super-Kamiokande, Homestake, and in GALLEX and SAGE, respectively, DS found only a moderate increase due to diffusion, 4%, 10%, 23%, 24% and 25%, respectively, in the above fluxes, which result in 10%, 10% and 2% increase in the predicted rates in Super-Kamiokande, Homestake, and in GALLEX and SAGE, respectively. Although the two diffusion calculations assumed a different initial solar chemical composition (see below) and BP approximated the diffusion of all elements heavier than  $^4\text{He}$  by that of fully ionized iron (the DS calculations followed the diffusion of each element separately and used diffusion coefficients calculated for the actual ionization state of each element at each shell in the sun as obtained from solving the local Saha equations), these cannot fully explain the above large differences. Recent independent diffusion calculations by Richard et al. (1996) obtained similar results to those obtained by DS as can be seen from Table III (we interpolated the results from the two models of Richard et al. to the initial chemical composition assumed by DS).

**Initial Chemical Composition:** The initial chemical composition influences significantly the solar evolution and the present density, chemical composition and temperature in the solar core, which determine the solar neutrino fluxes. In particular, the calculated radiative opacities, which in turn determine the temperature gradient in the solar interior, are very sensitive to the heavy elements abundances (the heavy elements are not completely ionized in the sun). Apart from the noble gases, only a few elements such as H, C, N and O, which were able to form highly volatile molecules or compounds, have escaped complete condensation in primitive early solar system meteorites (see, e.g., Sturenborg and Holweger 1990). Thus, the initial solar abundances of all other elements are expected to be approximately equal to those found in type I carbonaceous chondrites as a result of their complete condensation in the early solar system. Since the chemical composition of the solar surface is believed

to have changed only slightly during the solar evolution (by nuclear reactions during the Hayashi phase, by diffusion and turbulent mixing in the convective layer during the main sequence evolution, and by cosmic ray interactions at the solar surface) it has been expected that the photospheric abundances of these elements are approximately equal to those found in CI chondrites. Over the past decades there have been many initial disagreements between the meteoritic and photospheric abundances. In nearly all cases, when the atomic data were steadily improved and the more precise measurements were made, the photospheric values approached the meteoritic values. The photospheric abundances are now as a rule in very good agreement with the meteoritic values (Grevesse and Noels 1991; 1993). Since the meteoritic values represent the initial values and are known with much better accuracy (often better than 10%) than the photospheric ones, DS assumed that the initial solar heavy metal abundances are given approximately by the meteoritic (CI chondrites) values of Grevesse and Noels (1993) and adjusted the initial CNO and Ne abundances to reproduce their observed photospheric abundances. Also the unknown initial  $^4\text{He}$  solar abundance has been treated as an adjustable parameter. DS “predicted” its present photospheric mass fraction to be  $Y = 0.238 \pm 0.05$  in good agreement with the  $^4\text{He}$  surface mass fraction inferred from helioseismology:  $Y_s = 0.242 \pm 0.003$  (Hernandez and Christensen-Dalsgaard 1994). However, their formal error is highly misleading because of the great sensitivity of the result to the model of the solar atmosphere, the equation of state there and the atmospheric opacities. We estimate that at present the  $^4\text{He}$  mass fraction at the solar surface is not known from helioseismology better than  $Y_s = 0.242 \pm 0.010$ .. BP adjusted the initial solar composition to reproduce the present day surface abundances which, except for the CNO and the noble gases, were assumed to be represented by their meteoritic values.

The photospheric abundances of  $^7\text{Li}$ ,  $^9\text{Be}$  and  $^{11}\text{B}$  are smaller by a factor of nearly 150, 3 and 10, respectively, than their meteoritic abundances. The origin of such large differences is still not clear. They cannot be explained by nuclear burning during the Hayashi phase although significant Lithium burning does take place during this phase. They may be explained by rotational mixing (e.g., Richard et al 1996). Although the initial solar (meteoritic) abundances of Lithium, Beryllium and Boron are very small and do not play any significant role in solar evolution their depletion perhaps can provide a clue to the real history of the convection zone and the sun.

### **Equation of State:**

The equation of state is used to calculate the local density and temperature required to balance the gravitational pressure in the sun. Since the neutrino producing reactions in the sun depend strongly on temperature, their predicted fluxes depend strongly on the equation of state. DS have used an updated equation of state which is described in detail in DS96. It

is consistent with the new OPAL equation of state (Iglesias and Rogers 1996). The use of an improved equation of state reduce significantly our 1994 solar neutrino fluxes and improves the agreement between the sound speed in the solar core that we calculated from our SSM and the sound speed that is extracted from helioseismology. The agreement with the updated sound speed from helioseismology (Christensen Dalsgaard, 1996) is better than  $2 \times 10^{-3}$ , as is demonstrated in Fig. 1. It is significantly better than the agreement obtain/reported by other SSM calculations, but shares, with all other standard solar models (e.g., Bahcall et al. 1997), systematic deviations from the measured sound speed. Note also that helioseismology has confirmed only that the SSM describes quite well the ratio of pressure to density in the present sun but it does not provide any evidence that the production of  ${}^7\text{Be}$ ,  ${}^8\text{B}$  and CNO solar neutrino fluxes are well described by the SSM.

### 3 Neutrino Properties Beyond the Minimal SEM?

Counting rates in  $\nu_\odot$  experiments are formally given by

$$R = N_A \sum_i \phi_{\nu_\odot}(i) \int_{E_0} (dn_{\nu_i}/dE) \sigma_{\nu A}(E) dE \quad (1)$$

where  $N_A$  is the number of “active” atoms in the detector,  $\sigma_{\nu A}(E)$  is their cross section for neutrinos with energy  $E$ ,  $dn_{\nu_i}/dE$  is the normalized energy spectrum of neutrinos from reaction  $i$  in the sun and  $\phi_{\nu_\odot}$  is their total flux. Both,  $dn_{\nu_i}/dE$  and  $\sigma_{\nu A}$  follow directly from the standard electroweak theory and are independent of the sun. ( $dn_{\nu_i}/dE$  is practically the standard  $\beta$ -decay spectrum for the  $\beta$ -decays  $2\text{p} \rightarrow D e^+ \nu_e$ ,  ${}^8\text{B} \rightarrow 2\alpha e^+ \nu_e$ ,  ${}^{13}\text{N} \rightarrow {}^{13}\text{C} e^+ \nu_e$  and  ${}^{15}\text{O} \rightarrow {}^{15}\text{N} e^+ \nu_e$  and is a  $\delta$ -function for the electron captures  $e^7\text{Be} \rightarrow \nu_e^7\text{Li}$  and  $pep \rightarrow D \nu_e$ .) Thus *conclusive evidence* for new electroweak physics can be provided only by detecting at least one of the following signals:

1. Spectral distortion of the SEM  $\beta$ -decay spectrum.
2. Solar neutrino flavors other than  $\nu_e$ .
3. Terrestrial Modulations of solar neutrino fluxes.
4. A violation of the luminosity sum rule.
5. Rates which require negative  $\phi_{\nu_\odot}(i)$ .

So far, no such clear evidence has been provided by the  $\nu_\odot$  experiments.

**Spectral Distortions:** At present only Super-Kamiokande can test whether the spectrum of their detected  $\nu_\odot$ ’s is consistent with the  $\nu_e$  spectrum from  $\beta$ -decay of  ${}^8\text{B}$ . So far Super-Kamiokande (and Kamiokande before) has observed (Suzuki 1997) an electron recoil

spectrum from  $\nu_{\odot}e$  interactions which is consistent, with that expected from an undistorted  $^8\text{B}$  solar neutrino spectrum. Super-Kamiokande, which has been running since April 1, 1996, will soon have much more statistics allowing a more sensitive test.

**Flavour and/or Helicity Flip:** Neutrino oscillations or neutrino helicity flip can explain the solar neutrino observations (see, e.g., Voloshin these proceedings). However, no time variation which is predicted by a magnetic helicity flip has been detected by the  $\nu_{\odot}$  experiments. The present solar neutrino experiments can neither detect (Homestake, GALLEX and SAGE) nor distinguish (Super-Kamiokande) between different neutrino flavors. However, Super-Kamiokande will soon be able to examine with a high level of sensitivity (real time, high statistics) whether the  $^8\text{B}$  solar neutrino flux is time dependent. The sensitivity of Super-Kamiokande to temporal variation in the solar neutrino flux will be demonstrated by measuring the annual variation of the flux due to the annual variation of the distance of Earth from the sun. Any other confirmed variations which depend on the distance of Earth from the sun, on the orientation of the Earth relative to the sun (summer-winter) and on the (day-night, summer-winter) or distance dependence will signal with day Only future experiments like SNO will be able to detect other neutrino flavors.

**The Solar Luminosity Sum Rule:** If the sun derives its energy from fusion of Hydrogen into Helium and *if it is in a steady state* where its nuclear energy production rate equals its luminosity, then conservation of baryon number, electric charge, lepton flavor and energy requires that the total solar neutrino flux at Earth satisfies (e.g., Dar and Nussinov 1991):

$$\phi_{\nu_{\odot}} = \frac{2L_{\odot}}{Q - 2\bar{E}_{\nu}} \frac{1}{4\pi D^2} \geq 6.52 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}, \quad (2)$$

where  $D \approx 1.496 \times 10^{13} \text{ cm}$  is the distance to the sun,  $Q = 26.733 \text{ MeV}$  is the energy released when four protons fuse into Helium,  $\bar{E}_{\nu} = \sum E_{\nu_i} \phi_{\nu_i} / \sum \phi_{\nu_i}$  is the average energy of solar neutrinos and  $\bar{E}_{\nu} \geq 0.265 \text{ MeV}$  if the pp reaction in the sun produces  $\nu_{\odot}$ 's with the smallest average energy. Eq. (2) can be rewritten as a luminosity sum rule:

$$\sum_i (Q/2 - \bar{E}_{\nu_i}) \phi_{\nu_i} = S, \quad (3)$$

where  $S = L_{\odot}/4\pi D^2 = 1367 \text{ W m}^{-2}$  is the solar “constant”. A clear Violation of eq. (2) or the solar luminosity sum rule, can prove that lepton flavor is not conserved. The Gallium experiments with the low energy threshold of 233 keV, which makes them sensitive to almost all the SSM neutrinos, reported updated time-averaged capture rates of  $70 \pm 8 \text{ SNU}$  in GALLEX and  $72 \pm 12 \text{ SNU}$  in SAGE (see, e.g., Gavrin these proceedings). These rates, smaller than that predicted by SSMs are still consistent within the experimental uncertainties with  $76 \pm 2 \text{ SNU}$ , the “minimal” signal expected from eq. (2) if  $\sigma_{Ga} = (1.18 \pm 0.02) \times$

$10^{45} \text{ cm}^{-2}$ , and all the  $\nu_{\odot}$ 's were pp  $\nu$ 's. However, the  $^8\text{B}$  solar neutrino flux measured in Super-Kamiokande,  $\phi_{\nu_{\odot}} = (2.51 \pm 0.4) \times 10^6 \text{ cm}^{-2}$ , contributes another  $6 \pm 2 \text{ SNU}$  which increase the minimal expected signal in Gallium to  $82 \pm 3 \text{ SNU}$ . This somewhat larger rate is still consistent within  $2\sigma$  with the capture rates measured by GALLEX and SAGE, in particular if their rates are "recalibrated" using their Cr source experiments (Gavrin, these proceedings). However, the Gallium experiments leave no room for significant (SSM-like) contributions from  $^7\text{Be}$  and CNO solar neutrinos. This confirms the combined results from the Chlorine experiment at Homestake and from the Kamiokande and Super-Kamiokande experiments which seem to indicate that  $\phi_{\nu_{\odot}}(^8\text{B})$  is strongly suppressed (see below).

**Missing  $\nu_{\odot}$ 's in  $^{37}\text{Cl}$  ?:** Although the  $^{37}\text{Cl}$  experiment with an energy threshold of  $814 \text{ keV}$  is completely blind to the pp solar neutrinos it is sensitive to both the  $^8\text{B}$  neutrinos and the lower energy *pep*, CNO and  $^7\text{Be}$  neutrinos. However, while the expected signal from a  $^8\text{B}$  solar neutrino flux alone as measured by Super-Kamiokande is  $2.75 \pm 0.28 \text{ SNU}$ , the time-averaged counting rate in the  $^{37}\text{Cl}$  experiment is  $2.56 \pm 0.25 \text{ SNU}$  (see, e.g., Gavrin, these proceedings). Although the  $^{37}\text{Cl}$  experiment has not been "calibrated" with a neutrino source, the Cr source experiments of GALLEX and SAGE suggest that the accuracy of the radiochemical experiments is probably of the order of 10%, or better. Consequently, although the joint results from Homestake and Kamiokande do not provide solid evidence for "new electroweak physics" (e.g., Bahcall and Bethe 1991) they indicate that the combined contributions from  $^7\text{Be}$ , CNO and *pep* solar neutrinos is strongly suppressed in  $^{37}\text{Cl}$  compared with their SSM estimated contribution.

## 4 Are $^7\text{Be}$ Solar Neutrinos Missing?

Electron capture by  $^7\text{Be}$  into the ground state of  $^7\text{Li}$  produces  $862 \text{ keV}$  neutrinos. The threshold energy for neutrino absorption by  $^{37}\text{Cl}$  is  $814 \text{ keV}$ . Thus, absorption of  $^7\text{Be}$  neutrinos by  $^{37}\text{Cl}$  produces  $48 \text{ keV}$  electrons. The maximum energy of the pp solar neutrinos is  $420 \text{ keV}$ . The threshold energy for neutrino absorption in  $^{71}\text{Ga}$  ( $3/2^-$ ) is  $233 \text{ keV}$  into the ground state ( $1/2^-$ ) and  $408$  into its first excited state ( $5/2^-$ ). The produced electrons have therefore energies below  $187$  and  $12 \text{ keV}$ , respectively. If the theoretical cross sections for neutrino absorption near threshold overestimate significantly their true values then the predicted rates will significantly overestimate the expected signals in the Chlorine and Gallium experiments. An indication that final state interactions effects are not completely understood is provided by Tritium  $\beta$ -decay. Although final state interactions in Tritium  $\beta$ -decay have been studied extensively, they do not explain well the end-point  $\beta$ -decay spectrum ( $E_e \sim 18.6 \text{ keV}$ ). In all



recent measurements, the measured spectrum yields a negative value for the fitted squared mass of the electron neutrino. Final state interactions effects (screening of the nuclear charge by atomic electrons, exchange effects, radiative corrections, nuclear recoil against the electronic cloud, etc) in neutrino captures near threshold in  $^{37}\text{Cl}$  and  $^{71}\text{Ga}$  may be much larger because their  $Z$  values are much larger and because the de Broglie wave lengths of the produced electrons are comparable to the Bohr radii of the atomic K shells in Cl and Ga. If final state interactions reduce considerably the near threshold absorption cross sections of pp neutrinos in  $^{71}\text{Ga}$  (making room for the expected contribution of  $^7\text{Be}$  solar neutrinos in Gallium) and of  $^7\text{Be}$  neutrinos in  $^{37}\text{Cl}$ , perhaps they can make the solar neutrino observations of Super-Kamiokande and the Homestake experiments compatible. Such a terrestrial solution of the solar neutrino problem implies that experiments such as BOREXINO and HELLAZ will observe the full  $^7\text{Be}$  solar neutrino flux.

## 5 Astrophysical Solutions To The SNP

Even if the  $^7\text{Be}$  solar neutrino flux is strongly suppressed, it does not eliminate standard physics solutions to the solar neutrino problem: The ratio between the fluxes of  $^7\text{Be}$  and  $^8\text{B}$  solar neutrinos is given by

$$R = \frac{\phi_{\nu_{\odot}}(^7\text{Be})}{\phi_{\nu_{\odot}}(^8\text{B})} = \frac{\int n_e n_7 \langle \sigma v \rangle_{e7} 4\pi r^2 dr}{\int n_p n_7 \langle \sigma v \rangle_{p7} 4\pi r^2 dr}. \quad (4)$$

Because of the decreasing temperature and Be7 abundance as function of distance from the center of the sun on the one hand, and the  $\sim r^2$  increase in radial mass on the other, the production of  $^7\text{Be}$  and  $^8\text{B}$  solar neutrinos in the SSM peaks around an effective radius,  $r_{eff} \approx 0.064R_{\odot}$  ( $r_{eff}$  is approximately the radius within which 50% of the flux is produced). The SSM also predicts a ratio of electron to proton densities near the center of the sun,  $n_e/n_p \sim 2$ , consistent with helioseismology observations. Consequently, the SSMs predict

$$R \approx \frac{2 \langle \sigma v \rangle_{e7}}{\langle \sigma v \rangle_{p7}} \approx 1.27 \times 10^{-14} S_{17}^{-1} F_{17}^{-1} T_7^{1/6} e^{47.625/T_7^{1/3}}, \quad (5)$$

where  $F_{17}$  is the screening correction to the p-capture rate by  $^7\text{Be}$ ,  $T_7$  is the temperature in  $10^7 K$  at the effective radius and  $S_{17}$  is in  $eV \text{ barn}$  units. The SSMs yield  $T_7(r_{eff}) \approx 1.45$ . Using  $S_{17}(0) = 17 \text{ eV b}$  and  $\phi_{\odot}(^8\text{B}) = 2.51 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$  as observed by Super-Kamiokande, one can reproduce the SSM prediction (e.g., Dar and Shaviv 1996)

$$\phi_{\nu_{\odot}}(^7\text{Be}) = R \phi_{\nu_{\odot}}(^8\text{B}) \approx 3.7 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}. \quad (6)$$

Astrophysical solutions of the solar neutrino problem aim towards suppressing the value of  $R$ . Three alternatives are currently investigated:

**Plasma Physics Effects:** The effects of the surrounding plasma on nuclear reaction rates in dense stellar plasmas, and in particular on proton and electron capture by  ${}^7\text{Be}$  in the sun are known only approximately. Because of accidental cancellations the screening corrections in the Debye approximation (Salpeter and Van Horn 1969) to the rates of all nuclear reactions do not change the predicted  ${}^8\text{B}$  solar neutrino flux, although the screening corrections to the individual reactions are considerable (an enhancement by a factor  $F \approx e^{Z_1 Z_2 e^2 / k T r_D}$  where  $r_D$  is the Debye screening radius. The conditions required for the applicability of the Debye approximation are not satisfied in the solar core. In particular, because of the small number of particles within the Debye sphere,  $n \sim 1$ , plasma fluctuations may affect significantly the nuclear reaction rates. It is interesting to note that screening has the opposite effect on  $e$ -capture (reduction) compared with  $p$  capture (enhancement). In order to explain the deficit of  ${}^7\text{Be}$  solar neutrinos, plasma screening effects must enhance considerably the ratio between electron and proton capture by  ${}^7\text{Be}$ , relative to that predicted by the weak screening theory (Salpeter and Van Horne 1969). Perhaps a more exact treatment of screening, may change  $R$  considerably. This possibility is currently studied, e.g., by Shaviv and Shaviv (1996) using numerical methods and by Brown and Sawyer (1996) using quantum statistical mechanics techniques.

In principle, collective plasma physics effects, such as very strong magnetic or electric fields near the center of the sun, may polarize the plasma electrons, and affect the branching ratios of electron capture by  ${}^7\text{Be}$  (spin  $3/2^-$ ) into the ground state (spin  $3/2^-$ ,  $E_{\nu_e} = 0.863 \text{ MeV}$ , BR=90%) and the excited state (spin  $1/2^-$ ,  $E_{\nu_e} = 0.381 \text{ MeV}$ , BR=10%) of  ${}^7\text{Li}$ . Since solar neutrinos with  $E_{\nu_e} = 0.381 \text{ MeV}$  are below the threshold (0.81 MeV) for capture in  ${}^{37}\text{Cl}$  and have a capture cross section in  ${}^{71}\text{Ga}$  that is smaller by about a factor of 6 relative to solar neutrinos with  $E_{\nu_e} = 0.863 \text{ MeV}$ , therefore a large suppression in the branching ratio to the ground state can produce large suppressions of the  ${}^7\text{Be}$  solar neutrino signals in  ${}^{37}\text{Cl}$  and in  ${}^{71}\text{Ga}$ . However, such an explanation requires anomalously large fields near the center of the sun.

**Temporal and Spatial Variations in  $T$ :** Davis (1996) has been claiming persistently that the solar neutrino flux measured by him and his collaborators in the  ${}^{37}\text{Cl}$  radiochemical experiment is varying with time. Because of the possibility that neutrinos may have anomalous magnetic moments, much larger than those predicted by minimal extensions of the standard electroweak model, which can solve the solar neutrino problem, attention has been focused on anticorrelation between the solar magnetic activity (the 11 year cycle) and the  $\nu_\odot$  flux (see, e.g., Davis 1996). Also a day-night effect (e.g., Cribier et al 1986; Dar and Mann 1987)

due to resonant conversion of the lepton flavor of solar neutrinos which cross Earth at night before reaching the solar neutrino detector was not found by Super-Kamiokande. However, the basic general question whether the solar neutrino flux varies on a short time scale has not been fully answered by the first generation of solar neutrino experiments, mainly because of limited statistics. The SSM predicts that there is no significant variation of the solar neutrino flux on time scales shorter than millions of years. However, the sun has a differential rotation. It rotates once in  $\sim 25$  days near the equator, and in  $\sim 33$  days near the poles. Moreover, the observed surface rotation rates of young solar-type stars are up to 50 times that of the sun. It suggests that the sun has been losing angular momentum over its lifetime. The overall spin-down of a sun-like star by mass loss and electromagnetic radiation is difficult to estimate from stellar evolution theory, because it depends on delicate balance between circulations and instabilities that tend to mix the interior and magnetic fields that retard or modify such processes. It is quite possible that the differential rotation extends deep into the core of the sun and causes there spatial and temporal variations in the solar properties due to circulation, turbulences and mixing. Since  $R$  is very sensitive to the temperature, even small variations in temperature can affect  $R$  significantly without affecting significantly the pp solar neutrino flux (the  $^8\text{B}$  solar neutrinos will come mainly from temperature peaks, while the pp neutrinos will reflect more the average temperature). Another possibility is that the g-modes in the convective layer induce temporal and spatial variations in the solar core with a significant amplitude. In fact, a cross correlation analysis of the various data sets from the Homestake, Kamiokande, GALLEX and SAGE, shows an unexpected correlation: If arbitrary time lags are added to the different solar neutrino experiments, the cross correlation is maximal when these time lags vanish. Moreover, a power spectrum analysis of the signals shows a peak around 21 days, suggesting a periodical variation (Sturrock and Walther 1996). The effect may be a statistical fluke. However, it can also indicate a real short time scale variation in the solar core. Fortunately, Super-Kamiokande will soon provide the answer to whether the  $^8\text{B}$  solar neutrino flux is time-dependent or not (We propose to do a similar cross correlation analysis between the observed rates in different halves of the detector in order to see whether variations in the total counting rate, other than due to the eccentricity of the orbit of Earth around the sun, are due to statistical Poisson noise or reflect a time dependent signal).

**Mixing of  $^3\text{He}$ :** The SSM  $^3\text{He}$  equilibrium abundance increases sharply with radius. Cumming and Haxton (1996) have recently suggested that the  $^7\text{Be}$  solar neutrino problem could be circumvented in models where  $^3\text{He}$  is transported into the core in a mixing pattern involving rapid filamental flow downward. We note that if this mixing produces hot spots (due to enhanced energy release) they can increase the effective temperature for p capture by  $^7\text{Be}$  in a cool environment, reducing  $R$  while keeping the  $^8\text{B}$  solar neutrino flux at the observed level. Perhaps, helioseismology will be able to test that.

Cummings and Haxton (1996) also noted that such mixing will have other astrophysical consequences. For example, galactic evolution models predict  $^3\text{He}$  abundances in the presolar nebula and in the present interstellar medium (ISM) that are substantially (i.e., a factor of five or more) in excess of the observationally inferred values. This enrichment of the ISM is driven by low-mass stars in the red giant phase, when the convective envelope reaches a sufficient depth to mix the  $^3\text{He}$  peak, established during the main sequence, over the outer portions of the star. The  $^3\text{He}$  is then carried into the ISM by the red giant wind. The core mixing lowers the main sequence  $^3\text{He}$  abundance at large  $r$ .

## 6 The MSW Solution

Standard solar models, like the one calculated by Dar and Shaviv (1996), perhaps can explain the results reported by Kamiokande. However, if the neutrino absorption cross sections used by the radiochemical experiments are correct, then standard physics cannot explain an  $^{37}\text{Ar}$  production rate in  $^{37}\text{Cl}$  smaller than that expected from the solar  $^8\text{B}$  neutrino flux measured by Kamiokande (assuming that both results are correct). If the experimental results of Kamiokande and Homestake are interpreted as an evidence for such a situation (e.g., Bahcall 1994; 1995), they do imply new physics beyond the standard particle physics model (Bahcall and Bethe 1991). In that case an elegant solution to the solar neutrino anomaly is resonant neutrino flavor conversion in the sun, first proposed by Mikheyev and Smirnov (1986) (see also Wolfenstein 1978; 1979). It requires only a natural extension of the minimal standard electroweak theory and it is based on a simple quantum mechanical effect. Many authors have carried out extensive calculations to determine the neutrino mixing parameters which can bridge between the predictions of the standard solar models and the solar neutrino observations. They found that a neutrino mass difference  $\Delta m^2 \sim 0.7 \times 10^{-5} \text{ eV}^2$  and a neutrino mixing of  $\sin^2 2\theta \approx 0.5 \times 10^{-2}$  can solve the solar neutrino problem (see, e.g., Gavrin, these proceedings). These parameters, however, cannot explain the neutrino-oscillation-like signal which was reported by the LSND experiment (Athanasopoulos 1996).

## 7 Conclusions

The solar neutrino problem may be an astrophysical problem. An indication for that may come from observation of unexpected temporal variability of the solar neutrino flux by Super-Kamiokande or from helioseismology observations by SOHO and GONG. An indication may also come from cross correlation analysis of the time dependent of the counting rates in

GALLEX and Sage and of the counting rates of Kamiokande and Homestake. Such cross correlation analysis may test whether the time variation of the counting rates is statistical or physical. Deviations of the experimental results from those predicted by the standard solar models may reflect the approximate nature of these models (which neglect angular momentum effects, differential rotation, magnetic field, angular momentum loss and mass loss during evolution and do not explain yet, e.g., solar activity and the surface depletion of Lithium, Berilium and Boron relative to their meteoritic values, that may or may not be relevant to the solar neutrino problem). Improvements of the standard solar model should continue. In particular, dense plasma effects on nuclear reaction rates and radiative opacities, which are not well understood, may affect the SSM predictions and should be further studied, both theoretically and experimentally. Relevant information may be obtained from studies of thermonuclear plasmas in inertial confinement experiments. Useful information may also be obtained from improved data on screening effects in low energy nuclear cross sections of ions, atomic beams and molecular beams incident on a variety of gas, solid and plasma targets.

Better knowledge of low energy nuclear cross sections is badly needed. Measurement of crucial low energy nuclear cross sections by new methods, such as measurements of the cross sections for the radiative captures  $p + {}^7\text{Be} \rightarrow {}^8\text{B} + \gamma$  and  ${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$  by photodissociation of  ${}^8\text{B}$  and  ${}^7\text{Be}$  in the coulomb field of heavy nuclei are badly needed in order to determine whether there is a  ${}^8\text{B}$  solar neutrino problem.

The  ${}^{37}\text{Ar}$  production rate in  ${}^{37}\text{Cl}$  indeed may be smaller than that expected from the flux of standard solar neutrinos as measured by electron scattering in the Kamiokande experiment. In that case neutrino oscillations, and in particular the MSW effect, may be the correct solution to the solar neutrino problem. Only future experiments, such as SNO, Super-Kamiokande, BOREXINO and HELLAZ, will be able to supply a definite proof that Nature has made use of this beautiful effect.

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**Table Ia:** Comparison between the solar neutrino fluxes predicted by the SSM of BP95 and of DS96, and measured by the four solar neutrino experiments.

$\nu$ Flux	BP95	DS96	Observations	Experiment
$\phi_\nu(pp)$ [ $10^{10} cm^{-2} s^{-1}$ ]	5.91	6.10		
$\phi_\nu(pep)$ [ $10^8 cm^{-2} s^{-1}$ ]	1.39	1.43		
$\phi_\nu(^7Be)$ [ $10^9 cm^{-2} s^{-1}$ ]	5.18	3.71		
$\phi_\nu(^8B)$ [ $10^6 cm^{-2} s^{-1}$ ]	6.48	2.49	$2.51 \pm 0.23$	Super – Kamiokande
$\phi_\nu(^{13}N)$ [ $10^8 cm^{-2} s^{-1}$ ]	6.4	3.82		
$\phi_\nu(^{15}O)$ [ $10^8 cm^{-2} s^{-1}$ ]	5.15	3.74		
$\phi_\nu(^{17}F)$ [ $10^6 cm^{-2} s^{-1}$ ]	6.48	4.53		
$\Sigma(\phi\sigma)_{Cl}$ [ $SNU$ ]	$9.3 \pm 1.4$	$4.1 \pm 1.2$	$2.56 \pm 0.25$	Homestake
$\Sigma(\phi\sigma)_{Ga}$ [ $SNU$ ]	$137 \pm 8$	$115 \pm 6$	$70 \pm 8$	GALLEX
$\Sigma(\phi\sigma)_{Ga}$ [ $SNU$ ]	$137 \pm 8$	$115 \pm 6$	$72 \pm 12$	SAGE

**Table Ib** Characteristics of the BP95, DS94, and DS96 Solar Models in Table Ia (c=center; s=surface; bc=base of convective zone;  $\bar{N} = \log([N]/[H]) + 12$ ).

Parameter	BP95	DS94	DS96
$T_c$ [ $10^7 K$ ]	1.584	1.554	1.561
$\rho_c$ [ $g cm^{-3}$ ]	156.2	155.3	155.4
$X_c$	0.3333	0.3462	0.3424
$Y_c$	0.6456	0.6359	0.6380
$Z_c$	0.0211	0.01950	0.01940
$R_{conv}$ [ $R/R_\odot$ ]	0.712	0.7105	0.7130
$T_{bc}$ [ $10^6 K$ ]	2.20	2.10	2.105
$X_s$	0.7351	0.7243	0.7512
$Y_s$	0.2470	0.2597	0.2308
$Z_s$	0.01798	0.01574	0.0170
$\bar{N}_s(^{12}C)$	8.55	8.50	8.55
$\bar{N}_s(^{14}N)$	7.97	7.92	7.97
$\bar{N}_s(^{16}O)$	8.87	8.82	8.87
$\bar{N}_s(^{20}Ne)$	8.08	8.03	8.08
$T_{eff}$ [K]		5920	5803



**Table II:** Comparison between the SSM of Bahcall and Pinsonneult (1995) and of Dar and Shaviv (1996).

	BP95	DS96
$M_{\odot}$	$1.9899 \times 10^{33} \text{ g}$	$1.9899 \times 10^{33} \text{ g}$
$L_{\odot}$	$3.844 \times 10^{33} \text{ erg s}^{-1}$	$3.844 \times 10^{33} \text{ erg s}^{-1}$
$R_{\odot}$	$6.9599 \times 10^{10} \text{ cm}$	$6.9599 \times 10^{10} \text{ cm}$
$t_{\odot}$	$4.566 \times 10^9 \text{ y}$	$4.57 \times 10^9 \text{ y}$
Rotation	Not Included	Not Included
Magnetic Field	Not Included	Not Included
Mass Loss	Not Included	Not Included
Angular Momentum Loss	Not Included	Not Included
Premain Sequence Evolution	Not Included	Included
Initial Abundances :		
$^4\text{He}$	Adjusted Parameter	Adjusted Parameter
C, N, O, Ne	Adjusted Photospheric	Adjusted Photospheric
All Other Elements	Adjusted “Photospheric”	Meteoritic
Photospheric Abundances :		
$^4\text{He}$	Predicted	Predicted
C, N, O, Ne	Observed	Observed
All Other Elements	= Meteoritic	Predicted
Radiative Opacities	OPAL 1994	OPAL 1996
Equation of State	Straniero 1988?	DS 1996
Partial Ionization Effects	Not Included	Included
Diffusion of Elements :		
H, $^4\text{He}$	Included	Included
Heavier Elements	Approximated by Fe	All Included
Partial Ionization Effects	Not Included	Included
Nuclear Reaction Rates :		
$S_{11}(0)$	$3.896 \times 10^{-22} \text{ keV} \cdot \text{b}$	$4.07 \times 10^{-22} \text{ keV} \cdot \text{b}$
$S_{33}(0)$	$4.99 \times 10^3 \text{ keV} \cdot \text{b}$	$5.6 \times 10^3 \text{ keV} \cdot \text{b}$
$S_{34}(0)$	$0.524 \text{ keV} \cdot \text{b}$	$0.45 \text{ keV} \cdot \text{b}$
$S_{17}(0)$	$0.0224 \text{ keV} \cdot \text{b}$	$0.017 \text{ keV} \cdot \text{b}$
Screening Effects	Included	Included
Nuclear Equilibrium	Imposed	Not Assumed

**Table III:** Fractional change in the predicted  $\nu_\odot$  fluxes and counting rates in the  $\nu_\odot$  experiments due to the inclusion of element diffusion in the SSM calculations of Bahcall and Pinsonneault (1996), Dar and Shaviv (1994, 1996) and Richard, Vauclair, Charbonnel and Dziembowski (1996). The results of models 1 and 2 of RVCD were extrapolated to the initial solar composition which was used in DS96.

$\phi_{\nu_\odot}$	BP95	DS96	RVCD
$pp$	− 1.7%	− 0.3%	− 0.8%
$pep$	− 2.8%	− 0.3%	− 0.4%
${}^7\text{Be}$	+13.7%	+4.2%	+ 6.5%
${}^8\text{B}$	+36.5%	+11.2%	+10.7%
${}^{13}\text{N}$	+51.8%	+22.7%	+19.8%
${}^{15}\text{O}$	+58.0%	+24.0%	+20.8%
${}^{17}\text{F}$	+61.2%	+24.9%	+21.8%
Rates			RVCD
H2O	+36.5%	+11.2%	+13.3%
Cl	+32.9%	+ 9.5%	+12.3%
Ga	+ 8.7%	+ 2.6%	+ 3.7%